VOLUME XXIX NUMBER 5

THE

JOURNAL OF GEOLOGY

JULY-AUGUST 1921

DIASTROPHISM AND THE FORMATIVE PROCESSES

XIV. GROUNDWORK FOR THE STUDY OF MEGADIASTROPHISM

PART I. SUMMARY STATEMENT OF THE GROUNDWORK ALREADY LAID[1]

THOMAS C. CHAMBERLIN
Research Associate, Carnegie Institution of Washington

PART II. THE INTIMATIONS OF SHELL DEFORMATION

ROLLIN T. CHAMBERLIN
The University of Chicago

PART I. SUMMARY STATEMENT OF THE GROUNDWORK ALREADY LAID

INTRODUCTION

As set forth in the first of this series of articles, it has been their main purpose to develop into more explicit form the basal ideas that logically belong to an earth built up of planetesimals. Inevitably, the alternative ideas that have been based on the older concept of an earth of gaseo molten origin have been more or less constantly compared with them. The whole of the field has not yet been covered, but as the study now passes to a new and difficult phase, it is felt that it will be serviceable to assemble in brief, rather categorical statements such of the basal ideas already

[1] Published by permission of the Carnegie Institution of Washington.

developed as will form the groundwork for this next stage of the work, which will be a study of the megadiastrophism of the earth.

The introduction of the new term, megadiastrophism, calls for an explanation, if not an apology. It has already been found desirable by dynamic geologists to introduce the word "diastrophism," as a term of more comprehensive meaning than "deformation." The latter, while general enough in its etymological sense, has come to have a rather special meaning, by reason of its long usage to designate folding, faulting, and similar *declared* distortions of strata. It is not usually understood to denote those more intimate changes of form that take place in the deeper interior of the earth's body. To try now to make it include these would be at the risk of misinterpretation. But the new term diastrophism may be used to cover *any form of distortion of solid bodies*, and thus meet an imperative need.

There now arises a need for a still more comprehensive term which shall denote the diastrophism of the earth as a whole—or of large parts of it, such as continents and suboceanic segments—in a *collective* way without regard to the various special modes by which the diastrophism is effected. In the very nature of the case, the diastrophism of these great units will be composite and very complex, but we need to deal with them in a unitary way despite this complexity. The term megadiastrophism seems suitable for this purpose.

One of the most formidable obstacles in the way of bringing into actual use a new set of concepts where an old set has long had full possession of the thought, lies in the difficulty of really clearing the mind of *all the incidental factors* of the old concept, and of putting in their place *a full set* of the new. The difficulty does not lie so much with the main bold features of the new view as with the less obvious progeny of *derivative* concepts that must, in consistency, go out with the parent concept. In the study of any basal subject that has run far back into one's past thinking, a large brood of derivative concepts is quite sure to have been drawn out, but their connection with the parent idea is quite likely to have become obscure or to have passed entirely out of consciousness, so that the setting aside of the parent idea does not automatically

take them with it. It is not at all surprising, therefore, that, even in the most sincere endeavor to give true shape to a new issue under a new view for the purpose of a candid and hospitable test, some of the derivatives of the old view should unconsciously slip in and be treated as though they were offspring of the new. This, in reality, vitiates the whole test. The problem that has thus actually been fashioned and put to trial is a hybrid; it is not a true problem under either the old or the new view. For example, under the theory of a gaseo-molten earth, it was logically assumed that each spherical layer of the earth's interior was homogeneous; and hence it had a definite "melting-point."[1] There followed closely the inference that the material of such a layer must have a common state, either liquid or solid. From these logical derivatives of the primary assumption, far-reaching inferences were drawn in perfect consistency, and these, by years of association, have been woven into the web and woof of current thought with little consciousness that they are only dependencies of a cosmological postulate.

But if, on the other hand, the material of all such layers is very heterogeneous chemically, because it is an intimate mixture of planetesimal débris laid down at random, the logical inference is that each layer embraces *a wide-ranging group of solution temperatures* and has no single point of liquefaction. If it is subjected to a rising temperature, this would, at any given stage, cause the liquefaction of *only that fraction* of the material which was susceptible of liquefaction at the temperature reached, *not the "melting" of the whole layer*. This fraction would naturally be scattered throughout the mass of the layer and would give rise only to interstitial liquidity. The solution temperatures of the larger portion of the layer would not yet be reached, and this portion would remain solid. Now if the working mechanism of the body is so actuated by the joint force of internal and external stresses that graded pressures are brought to bear, greater below than above, and more or less intermittent, the disseminated liquid is likely to be kneaded out of the layer in the direction of least resistance and so leave the residue solid.

[1] In revised terms, as applied to interior conditions, a solution temperature or a narrow group of temperatures at which the constituents enter into mutual solution.

Now it will be seen that this second chain of derivatives is very different from the preceding chain and that the two are mutually exclusive. The links of the two cannot be mixed without the loss of all logical force. If mixed, the terms of the problem become a hybrid of incompatibles; such a chain does not exist in nature; it is not a real problem at all; it is merely a supposititious combination of incongruities.

The concept of isostasy gives rise to one set of derivatives, if based on the hypothesis of a crust floating on a liquid substratum inclosing a centrosphere of concentric homogeneous layers; and to quite a different set of derivatives on the hypothesis of a solid elastic earth whose internal material is heterogeneous and has suffered internal distortion.

The problem of the saltness of the sea has one set of subconcepts if the hydrosphere, at the outset, was as great as now or even greater, and quite another set if the hydrosphere started from a minimum and has grown steadily ever since and is growing still. To mix these throws the whole effort out of court. And so of not a few other earth problems of the more complex order.

In view of the difficulties of meeting the imperative requirements of consistency in working out such complex problems as the inner diastrophism of the earth, it is hoped that the following effort to reduce to brief convenient form the essential concepts already reached in the study of planetesimal accretion will be found serviceable. They are not a formal summary of the preceding articles nor drawn exclusively from them; some of them even have no dependence on the planetesimal hypothesis; they are merely found to be tributary to a satisfactory concept of megadiastrophism under the conditions of accretion. To make the statements brief and convenient, qualifications have been largely neglected and some statements may seem somewhat too baldly affirmative, but recurrence to the fuller discussions will, it is hoped, show that reasonable recognition has been made of legitimate grounds of doubt and needs of qualification. It is quite impossible here to accredit these propositions to those who have done most to develop them; they are merely assembled as propositions tentatively accepted as groundwork for further study.

GENERAL PROPERTIES OF THE EARTH

1. The solid elastic nature of the earth is accepted as having been put beyond serious question by the concurrent testimony of seismic waves, the body tides, the polar nutations, and collateral evidences.

2. The outer and major part of the earth is held to be minutely heterogeneous in chemical and physical composition, but yet, in a mechanical sense, sufficiently homogeneous to transmit seismic vibrations in legible form.

3. Some questions remain respecting the earth core; it is held to be dense and rigid; but earthquake waves traversing it do not, as yet, tell an unequivocal story. Possibly it is formed of concentric zones rather homogeneous in themselves but varying from one another; possibly, also, segregation of metallic matter toward the center has gone far enough to give a higher ratio of density to elasticity in this inner part than in the accretional zone above, and thus introduced seismic anomalies.

4. So far as now deducible, elasticity and rigidity increase toward the center faster than density. Since simple density segregation would scarcely carry a relative *increase* of rigidity and elasticity, this seems to imply a dynamic cause. The mean rigidity of the earth seems to be distinctly higher than that of steel.[1]

5. The major pulsation-period of the earth seems to be of the order of an hour but it is not yet precisely deducible from elastico-rigid-density data;[2] nor is the naturalistic evidence conclusive.[3] It may be near enough to commensurability with the semi-diurnal tide to strengthen it by resonance, but this is not certain.

6. The mode of motion of the poles in the earth is an index of high elastic rigidity. Schweydar has recently determined the

[1] Schweydar's recent determination is two and one-half times the rigidity of steel; he gives the rigidity of the central part of the earth as ten times that of the surficial part. "On the Elasticity of the Earth," *Naturwissenschaften* (1917), Potsdam, Germany, Part 38.

[2] On the influence of gravity on elastic waves, and in particular on the vibrations of an elastic globe, see T. J. A. Bromwich, *Proc. Lond. Math. Soc.*, Vol. XXX (1899).

[3] Nagaoka tried to deduce it from the eruptions of Krakatoa, *Nature* (May 26, 1907), pp. 89–91.

nutation period as 432.8 days.[1] This is so nearly commensurate with the fortnightly tide that there may be a resonance relation between them. The subnutation that has an annual period is probably the result of the seasonal shift of solar effects north and south of the equator.

7. The elastic nature of the body tide is accepted as practically demonstrated by the researches of Michelson, Gale, and Moulton, added to those of previous investigators.[2]

8. The water tides are held to spring in part from the body tide and in part from the direct attraction of the tide-producing bodies; their rise to notable value depends on the resonance of their basins.

THE TIME FACTOR

9. The arguments once urged against any great age of the earth because of the sun's short life, tidal action, etc., are held to be wholly invalid. An age somewhere between one billion and several billions of years seems best to fit in with astronomical and biological considerations. Ample time should be allowed for the evolution of star-clusters and the stellar galaxy, as well as life-evolution.

10. Estimates of the earth's age, based on current geological processes, require large corrections for the accelerating effects of present high reliefs and soil cultivation; in particular, for (*a*) increased vertical circulation, (*b*) more rapid cycles of evaporation and precipitation, (*c*) greater instability of vegetal clothing, (*d*) more rapid run-off, (*e*) deeper penetration of solvent action, (*f*) greatly increased soil waste, and (*g*) the much greater length of the low-relief periods than of the high-relief periods.[3] The required corrections are probably great enough to reconcile the geologic with the radioactive estimates.

11. For the computations used in the articles here summarized, a range wide enough to cover the uncorrected geologic as well as the radioactive estimates was used, as follows: (*a*) for the time since

[1] W. Schweydar, *Naturwissenschaften* (1917), Potsdam, Germany, Part 38.

[2] A. A. Michelson and Henry G. Gale, "The Rigidity of the Earth," *Jour. Geol.*, Vol. XXVII (1919), pp. 585–601.

[3] "The Quantitative Element in Circum-Continental Growth," Article VIII, *Jour. Geol.*, Vol. XXII (1914), pp. 516–28.

the beginning of the Paleozoic, from one hundred million to four hundred million years; (*b*) for that since the beginning of the Proterozoic, from three hundred million to twelve hundred million years; (*c*) for that since the earliest Archeozoic whose age has been estimated, from four hundred million to sixteen hundred million years.[1]

12. The time occupied in the evolution of terrestrial life is regarded as one of the most dependable evidences of the earth's age, though its testimony is of a rather general nature. Since the evolution from the early Paleozoic to the present is confessedly only a small part of the whole evolution, it was taken as 1/10 in the computations.[2]

13. Combining biologic, geologic, and radioactive estimates, the total period of life-evolution is taken roundly as lying between one billion and four billion years.[3]

14. The length of the period during which the rate of planetesimal infall was compatible with life, *previous* to the earliest determined Archean, is thus made to range between six hundred million and twenty-four hundred million years.[4]

15. Making allowance for the formative stage that preceded life-evolution, the whole age of the earth is taken tentatively as falling somewhere between three billion and five billion years.

All these estimates are of course only intended to serve working purposes in the light of the latest evidences; the whole matter is to be kept *sub judice* awaiting further light.

CONSIDERATIONS ADVERSE TO HIGH ESTIMATES OF DIASTROPHISM

16. Great thicknesses of shallow-water sediments do not necessarily imply great sinking of the crust. Measured in the usual way, thicknesses much greater than any observed may be laid down in the normal process of continental outgrowth without necessarily involving any crustal sinking at all.[5] Very thick

[1] "The Bearings of the Size and Rate of Infall of Planetesimals on the Molten or Solid State of the Earth," Article XIII, *Jour. Geol.*, Vol. XXVIII (1920), pp. 675–77.

[2] *Ibid.*, p. 675. [3] *Ibid.*, p. 676. [4] *Ibid.*

[5] "Foreset Beds and Slope Deposits," Article VI, *Jour. Geol.*, Vol. XXII (1914), pp. 271–72.

sediments, however, usually carry evidences of actual sinking, but such sinking must be determined on its own specific grounds.

17. Great sea-transgressions of the land do not necessarily involve great continental depressions; they are more or less due to general denudation, to shore cutting, and to sea-rise caused by sediment from the land.[1]

18. Effective base-leveling implies an absence of crustal movement while it is in progress.[2] It thus bears on the promptness and completeness of isostatic readjustments.

PERIODICITY OF DIASTROPHISM

19. Effective base-leveling is evidence that the earth-body is strong enough to stand the strain of ordinary loading and unloading for a long period without essential yielding; it thus implies that isostatic adjustments are periodic rather than continuous, and that diastrophism, in so far as it is assignable to such loading and unloading, is similarly periodic.

20. The stages occupied in base-leveling and sea-transgression were probably much longer than the intervening stages of active deformation.

21. The mechanism of isostasy implies that great basins once formed tend to remain basins permanently, and that great protuberances tend to remain protuberances except as worn down. Isostasy is not hospitable to great inversions of sea and land. To this there may be regional exceptions where great erosion is closely paralleled by great deposition.

22. Since the present isostatic status follows a period of great diastrophic readjustment, it is an open question whether the present degree of compensation is essentially a consequence of that diastrophism, or is a normal state approximately maintained at all times.

[1] "The Lateral Stresses within the Continental Protuberances and Their Relations to Continental Creep and Sea-Transgression," Article III, *Jour. Geol.*, Vol. XXI (1913), p. 585; "Rejuvenation of the Continents," Article IV, *Jour. Geol.*, Vol. XXI (1913), pp. 673–75.

[2] "The Rejuvenation of the Continents," Article IV, *Jour. Geol.*, Vol. XXI (1913) pp. 676–81.

23. The data assembled by Rollin Chamberlin[1] imply that prolonged loading and unloading are either (*a*) sufficient to cause diastrophism at long intervals, or else (*b*) act as triggers to set off other forces that were steadily accumulating during the quiescent periods. Whether loading and unloading are in themselves sufficient causes of deformation or not is a question on which studies in megadiastrophism are expected to shed decisive light.

THE TOTAL AMOUNT OF SELF-COMPRESSION OF THE EARTH

24. In spite of the foregoing conservative considerations, the amount of unequivocal deformation shown in Paleozoic and later strata alone is so large as to overtax all resources of diastrophism safely assignable to the cooling of the earth, and yet the very complex diastrophism of the earlier areas greatly exceeded this later diastrophism. The deformations since the middle of the Miocene are so great—in view of their lateness in the history of the earth—as to suggest that the causes of diastrophism are very persistent and very profound.

25. If we try to measure the total diastrophism by comparison with the total life-evolution, a result more than ten times that of the Paleozoic and later ages is implied, for diastrophism should have been very active in the formative ages and declined afterward, while life-evolution appears to have been accelerated as time went on.

26. If the intimate crumpling, close folding, and faulting of the Archean and Proterozoic terranes is made the basis of estimate, the total diastrophism must have been very great, but just how great it is impossible now to say.

27. If the present continents be looked upon as the outcome of a contest between sea-shelf outbuilding, on the one side, and inthrust from the oceans, on the other, the total diastrophism is clearly large, but very difficult to estimate definitely.

28. If the early earth be supposed to have been segmented in a natural mechanical way, and the existing continents and ocean basins interpreted as derivatives from these segments by

[1] "Periodicity of Paleozoic Orogenic Movements," Article VII, *Jour. Geol.*, Vol. XXII (1914), pp. 315–45.

outgrowth, thrust, and deformative shift, the total diastrophism appears even greater than that inferred from the preceding data.

The concurrent import of all lines of evidence is that the total diastrophism of the earth was very great, but a more comprehensive and quantitative mode of estimate is needed, and especially one that covers the diastrophism of the formative stages, in respect to which these lines are very weak.

DIASTROPHISM ESTIMATED BY PLANETARY COMPARISON

29. A comparative study of the volumes and densities of the earth and its neighbors affords an entirely independent mode of estimate and gives definite quantitative results.[1]

30. If the moon were built up of moon-stuff—having its present mean density of 3.34—to a sphere whose mass equaled that of the earth, it would have a volume of 430,353,000,000 cubic miles, while the actual earth's volume is only 259,924,000,000 cubic miles. To reduce the hypothetical moon-earth to the volume and density of the real earth would require a shortening of the radius of 725 miles and of the circumference of 4,555 miles.[2]

31. If Mars were built up of Mars-stuff at its present mean density of 3.58 to a spherical body of the mass of the earth, it would have a volume of 401,502,000,000 cubic miles. To compress this to a body of the density and volume of the earth would involve a shortening of its radius of 618 miles and of its circumference of 3,883 miles.

32. If Venus were similarly built up of its own material to a mass equal to that of the earth, its volume of 289,506,000,000 cubic miles would have to be shrunk radially 177 miles, and circumferentially 1,112 miles, to have the volume and density of the earth.

33. The earth, moon, Mars, and Venus revolve in a tract whose total width is less than 3 per cent of the radius of the planetary system. They were, therefore, probably formed under much the same dynamics, of much the same kinds of material, and in much

[1] "The Order of Magnitude of the Shrinkage of the Earth Deduced from Mars, Venus, and the Moon," Article X, *Jour. Geol.*, Vol. XXVIII (1920), pp. 1–17.

[2] *Ibid.*, p. 13.

the same way, and hence are closely comparable. There might have been some gradation of material, but since the earth is compared with the next outer and the next inner planet, any such gradation is largely equated in combining the results. These four bodies may therefore be taken as representing four stages of growth of a single body under the conditions that prevail at their mean distance from the sun, which is substantially the earth-distance.

34. The giant gaseous planets cannot properly be compared with these solid bodies without radical qualification, for the giants were probably gaseous from the start and never underwent the sifting necessary to cull out material unsuited to form the earth and kindred bodies (see 48 below). The evolution of the giant planets belongs to a distinctly different category.

35. Comparing the densities of the earth, Venus, Mars, and the moon as they now are, a marked increase of density with increase of mass is shown: to wit, the moon, with mass 0.0122 (earth = 1), has a density 3.34 (water = 1); Mars, with a mass 0.1065, has a density 3.58; Venus, with mass 0.807 (?), has a density 4.85 (?); and the earth, whose mass is unity, has a mean density 5.53.[1]

36. Closer inspection shows not only an increase of density with mass but *an accelerated rate of increase of density for each increment of mass*. This clearly implies that *their densities arise* from their own massiveness, an inference in harmony with No. 4 above.[2]

37. Under the kinetic theory of gases, the larger the mass, the greater its ability to hold light molecules. Greater proportions of intrinsically light matter were therefore almost certainly gathered into the more massive bodies. *They became dense in spite of a larger proportion of intrinsically light material.*[3]

38. Let it be noted that the acquirement of high density is not held to be a matter of simple mechanical compression; this was a conditioning factor in the process, but only that. There were probably added (*a*) progressive rearrangements and reorganizations of the material into denser forms as the stresses grew, including not only simple physical readjustments but the formation

[1] *Ibid.*, p. 10. [2] *Ibid.*, pp. 16–17. [3] *Ibid.*, p. 17.

of new compounds, new minerals, and possibly even new molecules and new atoms; (*b*) an increase of endothermic compounds as the temperature increased; (*c*) the removal of liquefied material and its heat of liquefaction; as also (*d*) the self-heating radioactive substances that helped to produce the liquidity. This process was essentially a metamorphic one, but in the deep interior the stresses and temperature rose to a much higher order than in the zone of observation, and the metamorphism is assumed to have been more radical.[1]

39. Simple pressure experiments are incompetent to determine the limit of self-compression in this broader sense. Such experiments cannot even cover the full range of metamorphic reorganization recorded in the observational zone. They are much less competent to set metes and bounds to the higher order of metamorphism under immensely greater stress conditions. At best they can only indicate how much of the observed effect is to be assigned to simple mechanical compression and how much to metamorphism in the interest of higher density.

40. To set the new view into sharp contradistinction to the old, let it be noted that the planetesimal earth is looked upon as a profoundly metamorphic earth with a minor igneous accessory, while the traditional earth is commonly regarded as a profoundly igneous earth with a minor surficial metamorphic subsidiary.

RESCRUTINY OF THE FORMATIVE PROCESSES

The importance of the results of planetary comparison made it seem imperative to rescrutinize the whole chain of postulates that lies back of them. Chief among these were the tenets of the planetesimal hypothesis itself. This hypothesis was therefore reconsidered from the ground up. At the same time competing hypotheses were retested, for these lie, in a similar way, back of the older views of diastrophism, whether their authors are aware of it or not. This restudy brought forth not only evidence confirmatory of previous views but supplementary considerations which need to be summarized here as part of the groundwork on which further study is to proceed.

[1] *The Origin of the Earth* (1916), chap. ix, "The Inner Organization of the Earth," pp. 226–40.

41. To follow accurately the logic of the planetesimal hypothesis, it is necessary to keep clearly in mind that its point of view is pre-eminently *dynamic*. Its type ideas are not based on *material forms*, but on *dynamic organizations*. This was set forth in explicit terms in the earliest full statement of the hypothesis.[1] In spite of this, the hypothesis has come to be more or less unconsciously regarded as dependent on a special interpretation of spiral nebulae, because these nebulae have been much used as illustrations of the type of deployment supposed to have been involved in the genesis of our planetary system, but the theory is not thus dependent, as was urged from the outset. It will stand or fall solely on its ability to explain the remarkable characteristics and relationships of our planetary system. The requirements imposed by these are so many and so exacting that no theory but the true one has any chance of fully meeting them. We may, of course, think they are met when they really are not. We hold it is quite sure, however, that in time the "vestiges of creation" will give convincing tests, and the essentials of the whole history of the earth will be read from beginning to end.

42. Two distinct types of planetesimal organization are recognized: In one, planetary nuclei, serving as collecting centers, revolve among the planetesimals and gather them in, forming bodies of notable size. In the other, there are no such collecting nuclei, and the formation of bodies of planetary size is a practical impossibility; the planetesimals remain small and constitute a multitude of minute secondaries.

43. Two distinct classes of planetesimal secondaries are recognized: (*a*) those which the parent body may develop *by its own genetic resources*, i.e., *monoecious* secondaries, and (*b*) those which can be developed only by the *co-operation* of another body serving as a second dynamic parent, i.e., *dioecious* secondaries.[2]

[1] In outlining the planetesimal hypothesis for the use of students in Chamberlin and Salisbury's *Geology*, Vol. II (1905), pp. 38–40, it was specifically pointed out that the planetesimal condition may arise in different ways, as from a gaseous nebula of the Laplacian type, or a meteoritic swarm of the Lockyer type. An origin from a spiral nebula was made the leading type for reasons specified, but to this was added: "While this will be followed as the type view, let it be distinctly noted that the planetesimal doctrine of accretion does not stand or fall with this particular conception" (p. 40).

[2] *The Origin of the Earth* (1916), "Celestial Kinships," pp. 101–2.

Monoecious secondaries may arise as orbital ultra-atmospheres[1] do, and in similar ways, and are normally minute. They thus probably attend all stars in prodigious numbers but small mass. Dioecious secondaries are assigned to the dynamic action of a passing body on an eruptive sun by first stimulating an effective outburst and then drawing the projected matter into orbits about the mother-body, a purely dynamic function. The eruptions are quite sure to take place by successive impulses, and a part of each belch is likely to remain under self-control and act as a collecting center for the more scattered planetesimal part. Thus the main mass will be gathered into a comparatively few, rather large planets.

44. While thus *monoecious* systems may be nearly universal, *dioecious* systems can arise only when the necessary dynamic encounter takes place. Close approaches of stars are rare events; there is, therefore, no reason to suppose that planetary systems *like our own* are common in the heavens. Only one such is known. Still, rarely as one star closely approaches another, the multitude of stars and the great length of celestial time makes possible a fairly large number of even this very peculiar class of secondaries. It is a logical error to base arguments on the assumption that planetary systems of this type are universal or even necessarily frequent attendants of stars.

45. The cosmological rescrutiny brought out in stronger terms than before the extreme improbability that a planetary system like our own would arise from any form of centrifugal action in a condensing gaseous or quasi-gaseous nebula. The principles of the kinetic theory of gases, combined with the dynamic considerations that lie back of the Roche limit[2] and of the new criterion of Moulton,[3] indicate that all such action would result in minute secondaries without effective collecting nuclei, a condition which practically inhibits the formation of large planets.[4]

[1] *The Origin of the Earth* (1916), "Celestial Kinships," p. 21.

[2] F. R. Moulton, "On the Application of Roche's Limit and a New Criterion of Somewhat Similar Character," *Astrophys. Jour.*, Vol. XI (1900), pp. 120–26.

[3] *Ibid.*

[4] "Selective Segregation of Material in the Formation of the Earth and Its Neighbors," Article XI, *Jour. Geol.*, Vol. XXVIII (1920), pp. 137–44.

46. Planetary generation by the dioecious method is not confined to the approach of one *star* to another; bodies less massive than stars, if they make sufficiently close approaches, are competent to develop planetary systems. Only 1/745 part of the mass of the sun was required to form the planets of our system. The critical point in such cases is the ability of the small passing body to impart the requisite revolutionary momentum.[1]

47. New potentialities of projection from the sun have recently been disclosed. Twice during 1919, Pettit observed that erupted calcium vapor ascended by *a succession of accelerating impulses*. In one case, the ejected calcium vapor increased its outward velocity from 5.5 kms. per second to 60 kms. per sceond; in the other, from 37 kms. per second to 163.9 kms. per second. In both cases, the calcium was moving at its highest velocity when it ceased to be visible, high above the sun, probably either from cooling or from scattering, or both.[2]

DIVERGENCIES IN THE MODES OF PLANETARY CONDENSATION

48. The planetary nuclei diverged into two lines of descent almost as soon as they emerged from the sun. The nuclei that were massive enough to remain hot and gaseous at all stages, and to hold practically all molecules that came within their control, naturally grew to be giant planets. Nuclei that were not massive enough to hold all the solar gases, but in the main only the heavier ones, such as later made up the stony and metallic bodies, followed a much more selective career. This was a very vital matter, for the solar gases, constituted as they were, could not condense directly into bodies of the composition of the earth; a preliminary sifting was indispensable.[3]

49. A further divergence soon followed in this sifted class. A few of the larger nuclei were only incompletely sifted; so that they retained relatively small amounts of gases of the atmospheric

[1] "Multiple Phases of the Planetesimal Hypothesis," *ibid.*, pp. 149–50.

[2] Recent Disclosures Bearing on the Solar Parentage of the Planets," *ibid.*, pp. 145–49; Edison Pettit, "The Great Eruptive Prominences of May 29 and July 15, 1919," *Astrophys. Jour.*, Vol. L (October, 1919), pp. 206–19.

[3] "The Physical Phases of the Planetary Nuclei during Their Formative Stages," Article XII, *Jour. Geol.*, Vol. XXVIII (1920), pp. 481, 487–89.

type. In most cases, however, the nuclei were unable to hold any appreciable amount of such gases. Some of the smallest could not hold the hot vapors of even stony and metallic substances. This would have led to their complete dissolution but for the fact that, on emergence from the sun into interplanetary space, they promptly condensed into *clouds of precipitates and these soon gathered into precipitate aggregates*. These, being much larger and less active than the molecules of the previous vapors, were held under control and collected into planetoids.[1]

50. The formation of precipitates and precipitate aggregates of stony and metallic substances apparently played an important part in the condensation of planetary nuclei. As such precipitates appear to be forming now in the photosphere of the sun, it is assumed that they would be formed freely in solar gases projected into planetary space. Such aggregates would act as Brownian particles and the condensation would not be strictly gaseous. If the nuclei later passed into the liquid state, crystalline and concretionary aggregates would probably form and give rise to a solid-liquid Brownian mixture. The descent was therefore that of Brownian mixtures of different types rather than simple gaseous condensation.[2]

51. Each planetary nucleus must have inherited internal motions from its solar state and from its ejection, and this must have promoted cooling and precipitation during the first critical stages. Later, convectional movements were added and continued the precipitation. The inherited motions must have been more or less asymmetrical and this tended to give asymmetry to the core as it solidified.[3]

52. The inherited motions and the sifting processes were sources of hazard to each small nucleus. Probably the smallest planetoids and satellites now seen were the smallest that could be formed in this way. The spheres of control of even small nuclei were, however, surprisingly large, and this was doubtless the saving

[1] "The Physical Phases of the Planetary Nuclei during Their Formative Stages," Article XII, *Jour. Geol.*, Vol. XXVIII (1920), pp. 492–98.

[2] "The Formation of Precipitates and of Brownian Mixtures," *ibid.*, pp. 489–92.

[3] "The Motions Inherited from the Solar Eruption," *ibid.*, pp. 483–87.

factor. The sphere of control—as against the sun at the distance of the earth—of a mass 1/20 of that of the earth is 458,000 miles in diameter. A mass no greater than 0.000,000,296 of the mass of the earth has a sphere of control 8,200 miles in diameter (MacMillan). The functions of spheres of control in the genesis of planets are a feature that has been too much overlooked.[1]

53. Asymmetry in a planetary core was likely to make itself felt in the distortion of the mass later built upon it. The inherited notion that the earth core, if liquid, would be merely a melt whose solidification would have to await the progress of freezing from its surface downward belongs to an old order of thought. The solidifying process should rather be studied as progressive supersaturation and precipitation.[2] The formation of the solid core doubtless depended chiefly on the order in which the various possible minerals were formed and the extent to which they settled toward the center. The inherited and convectional motions doubtless affected the lodgment of the precipitates and rendered the growth of the core more or less asymmetrical.

54. Such external forces as gave rise to changes in the rate of rotation, or produced tides or nutations, must have played their part in distorting the forming core.[3]

THE SIZE OF THE PLANETESIMALS

55. At the outset, the planetesimals were merely the molecules of the scattered solar gases or the minute precipitates formed from these or else the molecules which escaped later from the nuclei. Starting thus small, and conditioned by their wide dispersion, their growth was necessarily not only slow but precarious.[4]

56. The Zodiacal Light is reflected by minute particles that probably have orbits of the planetary type, and hence are in fact

[1] "Table of Dynamic Properties," *ibid.*, p. 478. For function of spheres of control, see Article XI, *ibid.*, pp. 128–34.

[2] "The Critical Conditions That Controlled the Passage of the Nuclei into Collecting Cores," Article XII, *ibid.*, pp. 477–500.

[3] "Exterior Agencies That Affected the Planetary Cores during Their Formation and Afterward," *ibid.*, pp. 500–504.

[4] "The Nature of the Planetesimals at the Start," Article XIII, *ibid.*, pp. 666–71.

planetesimals. If they are planetesimals left over from the formation of the planets, they are surely old enough to have grown to the largest practicable sizes; but, in spite of this, they are certainly quite small. If they have had a more recent origin, they should still represent normal growth. In any case, they add their testimony to the smallness of planetesimals.[1]

57. The restudy of cosmological processes led to a new view as to the relations of the erratic elements of the solar system, the meteors, meteorites, and comets, to the normal elements, the planets, planetoids, planetesimals, satellites, and satellitesimals, to the effect that they were all formed by the same type of dynamic action, save that the former were given erratic orbits, while the latter were given concurrent orbits. The ways in which this difference arose are given in the original discussion. These give a unitary view to the whole solar system. Now under them, chondrules are interpreted as aggregates of stony and metallic precipitates from solar gases, growing in a manner similar to that of the planetesimals. If so, the sizes of chondrules and planetesimals should be about the same. Chondrules vary in size from walnuts down to dust particles, millet seed being mentioned as representative. Their history differs in some features from that of meteorites, and they might be called meteoresimals to distinguish them. They seem to be immensely more numerous than meteorites; probably at least a hundred million of these meteoresimals "burn out" in the upper air as "shooting stars" for every meteorite that reaches the ground.

58. Meteorites proper are interpreted as fragments of erratic bodies disrupted by the extremes of heat and cold they suffer at the two ends of their very elliptical orbits. The parent bodies are held to have been formed by the aggregation of precipitates in a way similar to the aggregation of planetoids (No. 49 above), except that the original material was given very diverse and elliptical orbits.[2] Under this view, it is not the meteorites but the chondrules that are analogous to the planetesimals.[3]

[1] "The Zodiacal Planetesimals," Article XIII, *Jour. Geol.*, Vol. XXVIII (1920), p. 672.

[2] "The Testimony of the Aberrant Bodies of the Solar System," *ibid.*, pp. 696–701.

[3] *Ibid.*, pp. 697–98.

59. The size of planetesimals is not really important in considering the heating effects of their infall, for what might be gained by their aggregation into large sizes would be lost by the lessened frequency of their infall, but to round out the inquiry a study was made of the effects of the infall of supposedly large bodies.

60. The great pit and the scattered material of the famous Meteor Crater (Coon Butte), Arizona, the greatest of accessible examples of its kind, show that the impact of a large body—probably meteoritic or cometic—caused extremely little melting but yet great excavation, much upturning and wedging aside of strata and wide scattering of débris. Its lesson is that the impact of such bodies converts their energy of motion *mainly into new forms of mechanical work*, and very subordinately into melting.[1]

61. On the supposition—not in fact accepted—that the craters of the moon are pits formed by infalling bodies, the proper inference from the observable effects is the same as that from Meteor Crater. The steep-walled pits and the great radiating lines of débris are direct evidence of great mechanical effects. The lofty walls of the pits show no signs of the collapse that should attend great melting. The evidence of lava flows, in proportion to the number and size of the craters, is not remarkable on the most favorable interpretation. The level tracts, interpreted as lava, may be merely débris plains. The lunar Alps, Apennines, and other mountain ranges of the moon imply at least a crust stout enough to sustain such great elevations. Nothing observable definitely implies a holo-molten state.[2]

MELTING EFFECTS OF PLANETESIMAL INFALL

62. The planetary nuclei undoubtedly picked up some planetesimals that had wide-ranging orbits, but the larger portion specially related to the earth were distributed in the form of a ring around the sun about 55,000,000 miles in breadth, 58,000,000 miles in depth, and 292,000,000 miles in length. All these planetesimals had their own independent orbits, and were sustained by their own revolutionary energy. Their condition was antithetical to the collisional and collapsing habit of molecules in a gaseous

[1] "The Testimony of Coon Butte or Meteor Crater," *ibid.*, pp. 686–89.

[2] "The Questionable Intimations of the Craters of the Moon," *ibid.*, pp. 690–94.

organization. They were subject to collision with one another, indeed, but their sparse distribution made the contingency less immanent than might easily be imagined. When collisions did occur, rebounds were more probable than mutual coherence; permanent unions were only probable when their relative speeds and other conditions were specially favorable. After union, they were liable to be driven apart again by succeeding collisions. Ultimate capture by the earth core was probable, but even in this case only as their orbits favored. They were perturbed by all the attractions of the solar system. These, on the whole, favored capture by the earth nucleus but not in all cases. The process of collection was intricate, indirect, and slow.[1]

63. As a step toward realizing the sparseness of the planetesimals and the time required for their collection, let them be supposed to stand still as at first distributed, while the earth nucleus, taken as a net 6,000 miles in diameter, sweeps through them at 18 miles per second. To expedite the work, let the path of this net be so shaped and shifted by some demon that it will clean up an entirely new swath at each revolution. Even then it would take about 100,000,000 years to sweep up all the planetesimals.[2]

64. To try, as a next step, the most rapid natural way, let the planetesimals act as though particles of a gas, collapsing on the track of the nucleus after each sweep—though that is far from their habit—and let each sweep, as before, clear a path 6,000 miles in diameter at the rate of 18 miles per second. It would then take about 260,000,000 years to gather in 90 per cent of the planetesimals; to sweep up all would require an indefinite period.[3]

65. The real case was much less favorable. The planetesimals and the nuclei were moving in the same general direction, at somewhat similar speeds. They could thus come together, as a rule, only as one overtook the other, or as their paths converged, a relatively slow method. They attracted one another but this did not necessarily bring them together, for their orbits might become so adjusted to one another that they merely became traveling companions, like the earth and the moon. Mutual attractions

[1] "The Intimations of the Planetesimal Mechanism," Article XIII, *Jour. Geol.*, Vol. XXVIII (1920), pp. 677–78.

[2] *Ibid.*, p. 678. [3] *Ibid.*, p. 679.

would constantly give rise to perturbations and these, on the whole, would favor the gathering in of the planetesimals, but just how fast is beyond the reach of rigorous computation. It can only be reached roughly by approximations. A period somewhere between one billion and three billion years seems most probable.[1]

66. While the total heat of planetesimal infall was great, the melting effects were conditioned by the rate of fall and by the extent of atmospheric surface into which they fell. At the stage when the earth was one-third grown, there would remain to fall in 4×10^{26} planetesimals averaging 1/50 lb.; or about 3×10^{15} planetesimals per square foot of earth surface. Taking the radio-bio-geologic estimate (2.4×10^9 years), as the time, the average rate of plunge into the upper part of each one-square-foot air-column would be one planetesimal in 6.7 days. Even at the time estimate based on the older geologic scale—probably much too short—a planetesimal would fall into the top of each square-foot air-column not oftener than once in 40 minutes. Now in the upper air, half the heat would be promptly radiated outward, and the rest would act at a disadvantage in heating the earth's surface some miles below. The mean intervals between falls would quite surely be much too great to produce the melting of the earth's surface.[2]

For a cross test, let the method be reversed by selecting a rate supposed to be sufficient to produce melting and testing this by the time. Let it be supposed that one fall per second per square-foot air-column would have been a melting rate. All the planetesimals would, at this rate, have been collected in a little over 4,000 years, an impossibly short time. It can scarcely be held that a rate of one fall per hour per column would produce surface melting; and yet, at that rate, all would have fallen in less than 15,000,000 years. We found that the impossibly speedy demon-directed method required 100,000,000 years. The melting of the surface during the last two-thirds of the earth's growth seems out of the question.[3]

[1] *Ibid.*, pp. 679–81.

[2] "The Rate of Planetesimal Infall," *ibid.*, pp. 681–86.

[3] *Ibid.*, pp. 683–86.

67. The protracted rescrutiny of the cosmological postulates back of the planetary comparison was made to see if the results of that comparison needed any serious modification or qualification. It was found that the total self-compression should be placed somewhat higher than the high figures given by the comparison, on account of the larger proportion of light material which the larger bodies gathered in. As the amount had previously been found to be unexpectedly large, the correction may be treated simply as a margin of safety. The trustworthiness of the comparative method seemed to be greatly strengthened by the rescrutiny; the deductions from the planetary comparison are therefore regarded as firm groundwork for further study.

THE DIASTROPHIC RESOURCES OF A PLANETESIMAL EARTH

68. An earth built of planetesimal dust settling from the air in a mixed state would retain, to an almost ideal degree, its latent resources for subsequent chemical combination and physical reorganization. It would retain also about as much as possible of its potential energy of position, for the accessions would be very loose as first laid down. In strong contrast to this, the resources of a molten earth would be dissipated in large measure while still in the fluid state. The molten globe spent its energies in a hot youth; the cooler planetesimal earth conserved its resources for its later life.

69. In a molten earth, the high heat would be the master factor; its rate of dissipation would set the pace of progress. In a planetesimal earth, the strength of the solid material would be the ruling factor. Self-compression would take place only as this was overcome. Heat, of course, would be developed, but only as the yield of the solid matter permitted; it would be merely an incident of the process and would help to stay the process until it was taken care of.

70. In a dust-built earth, self-compression began as soon as a new layer was laid on an old one. Thereafter, compression continued by stages and intervals as long as loading continued. Diastrophism therefore ran through the whole formative history and was doubtless more active during the stages of growth than since.

71. It seems inconsistent with the ultimate constitution of matter, as now understood, to assign any limit to compression so long as pressure increases and there is any way by which the energy of organization can escape or take a new form of greater density. As energy continues to escape from the earth, and as there still remain resources of reorganization into denser forms—at least in the outer part of the earth—diastrophism is probably yet far from the end of its career. It is probably competent to rejuvenate the continents for eras yet to come.

VULCANICITY AS A DIASTROPHIC AUXILIARY

72. Our planetary system, embracing nearly a thousand bodies all told, presents a great graded series in which the largest mass is many million times that of the smallest.[1] There is also a gradation in physical state. At the upper extreme, Jupiter is dominantly fluid; at the lower extreme, the planetoids and satellites are atmosphereless solids; in the middle, gases, liquids, and solids are combined. The earth is near the middle but dominantly solid. The dividing line, where fluids and solids might be supposed to be critically balanced, lies considerably above the earth in the series. The subordination of the fluid element in the earth is assignable to certain restraining factors imposed by the rigidity of the material. These give rise to a partition of the energy set free by self-compression, so that only a portion of it manifests itself as temperature. A portion becomes refixed in endothermic compounds; a portion is consumed as latent heat of liquefaction and is forced into higher horizons where a solid state is resumed and the liquefying energy is again set free and readily discharged, while a third portion is probably consumed in physical and, perhaps, even atomic reorganization. The joint effect is the persistent removal of liquidity and the conservation of solidity. The whole is a profound metamorphic process. The special processes of vulcanism are thus looked upon as subsidiary to the metamorphic-diastrophic processes, but still as important auxiliaries.

[1] "The Physical Phases of the Planetary Nuclei during Their Formative Stages," Article XII, *Jour. Geol.*, Vol. XXVIII (1920), table I, p. 476.

73. Since the formation of mutual solutions of rock material within the earth affects only such part of the mixed matter as becomes soluble under the contacts and conditions present, and since the solid state is resumed at or near the surface, *magmatic generation* is the matter of primary moment in the history as well as the philosophy of magmatization. Magmatic *differentiation* belongs essentially to the reverse process, and is dependent on the generative process.

74. The temperature curve of the interior, under this view, does not depend primarily on cooling from the surface or on the arrest of a convectional circulation, but on dynamic action within the body itself, starting with the restraints of inherited solidity in the clastic matter and adding new restraints at intervals later, by transformations of such a nature as to fit a part of the mixed material for a higher state of solidity, while a part was liquefied and sent to the surface to resume solidity there.

75. The gases and gas-producing substances entrapped by the burial of minutely mixed planetesimal matter should have been well-nigh a maximum. Subsequent processes of partial liquefaction and extrusion should have set these gases free, and they should have joined whatever liquid material was in process of formation. The magmas should thus have been rich in gases; sometimes becoming explosive. A large gaseous factor is therefore held to be characteristic of the vulcanism of an earth so built.

76. On the other hand, during the protracted boiling of a gaseo-molten earth, potential gases should have been set free to a maximum, and all gases should have been brought to the surface by convection, whence they should have escaped to the fullest extent consistent with gravity, because of their hot state. There should have remained in the boiled liquid merely the equilibrium quantity required to balance the partial pressures of the atmosphere.[1] Laboratory melts of like material under like conditions should indicate the limited amount of this. The cooled mass could scarcely have carried those abundant supplies of gas that have been so amply manifested by the extrusive action of all the

[1] Rollin T. Chamberlin, "The Gases in Rocks," *Jour. Geol.*, Vol. XVII (1909), pp. 565–68.

geologic ages. If the lunar craters are volcanic, as we assume, the evidence against a molten moon becomes still more imperative, for even in its cold, mature state the moon cannot hold free volcanic gases. All such gases should have escaped while the moon was still hot and boiling, and it should later have cooled to a smooth, gasless globe, singularly unfitted for the explosive action which its surface implies.[1]

CLUES FROM SURFICIAL DIASTROPHISM

77. The diastrophism of a solid earth should have been a unit, in all its great essentials. The deformations of the shell should have been intimately related to the diastrophism within the shell, if indeed not largely dependent on it. The mode of junction of the under surface of the shell with the upper surface of the interior mass should be especially instructive. One of the newer methods of study has disclosed the important fact that very notable downward protrusions are developed. These are defined by plunging zones of accommodation that are at least suggestive. The intimations of these are herewith added as Part II, since these seem to belong with this résumé of ground work for megadiastrophic study. Other studies in the zone of observation offer clues of great value; indeed, no line of inquiry lacks them. Two of these are very specially related to the study of inner diastrophism: the experiments of Adams[2] that point toward a higher degree of rigidity than was accepted previously, and the contributions of Van Hise[3] and Leith[4] to the methods of metamorphism, especially the selective and rejective phases of anamorphic action, which point toward methods of reorganization very like the more radical selective and rejective metamorphism assigned to the deep interior of the earth.

[1] Article XIII, *Jour. Geol.*, Vol. XXVIII (1920), pp. 694–95.

[2] Frank D. Adams, "An Experimental Contribution to the Depth of the Zone of Flow in the Earth's Crust," *Jour. Geol.*, Vol. XX (1912), pp. 97–118; F. D. Adams and J. A. Bancroft, "On the Amount of Internal Friction Developed in Rocks during Deformation, and on the Relative Plasticity of Different Types of Rocks," *Jour. Geol.*, Vol. XXV (1917), pp. 597–637.

[3] C. R. Van Hise, "A Treatise on Metamorphism," *Monogr. 47, U.S. Geol. Survey* (1904).

[4] Leith and Mead, *Metamorphic Geology* (1915).

PART II. THE INTIMATIONS OF SHELL DEFORMATION

As the result of field studies in Pennsylvania in 1905, the crustal shortening involved in the folding of the Appalachian Mountains west of Harrisburg was found to have been fifteen miles. Computations based upon this shortening and the consequent upbowing seemed to indicate that the shape of the deformed section was that of a triangular prism or wedge pointed downward.[1] Two sides of the wedge were found to converge beneath the mountainous tract till they came together under the middle portion of the deformed belt at a depth of thirty-two miles. No consideration whatever of stress-and-strain relations entered into the deduction of this wedge-shaped form. It came out directly from the graphic treatment of the field measurements, quite irrespective of any theory of mechanics, or of the nature of diastrophism; in fact, the result came as a distinct surprise. It was soon seen, however, that the shape was in harmony with the principles of fracture under essentially uniform horizontal compression.

The key to the method used in this inquiry lay in the axiomatic proposition that there must be a definite relation between the thickness of the deformed shell, the horizontal shortening which this shell has suffered, and the amount of resulting vertical bulge, on the assumption that there has been no notable compacting of materials.[2] When the horizontal shortening and the consequent upswelling have been determined from field measurements, the thickness of the deformed shell can readily be calculated. The most important outcome of the method is that it gives the under-configuration of the deformed shell in addition to other qualities. It is from this feature that the most important intimations relative to the deeper diastrophism are drawn.

Besides the under-configuration of the deformed shell, the following generalizations seem to be warranted: (*a*) Sharp folding

[1] Rollin T. Chamberlin, "The Appalachian Folds of Central Pennsylvania," *Jour. Geol.*, Vol. XVIII (1910), pp. 228–51.

[2] For a discussion of this and other possible qualifying factors, see *Jour. Geol.*, Vol. XVIII (1910), pp. 236–37, and also "The Building of the Colorado Rockies," *Jour. Geol.*, Vol. XXVII (1919), pp. 235–38, 244–47.

and much crustal shorting indicate the deformation of a thin shell; otherwise the resulting upward bulging would be enormous. (*b*) Open, gentle folding may signify either a thin shell or a thick shell, according as there has been little or much upbowing. (*c*) For a given crustal shortening, the greater the vertical uplift the thicker the shell which has been actively deformed.

The detection of the wedgelike shape of the deformed mass led to a consideration of the nature of the plunging planes which outline the block. If the wedge was defined by fracturing, the borders, as shown by the Daubrée experiment,[1] by the familiar crushing-strength tests upon building stones, as also by an analysis of the stress-strain relations, should be fault planes dipping beneath the deformed block at angles in the general vicinity of 45° though in most cases somewhat less. This is the result to be expected in a case of non-rotational strain, in which the axes of strain do not change position with respect to the axes of stress. If the developing strain be rotational in character, the angles of the shearing planes will be lowered from 45°, in proportion to the extent of the rotational element.[2] If, on the other hand, definite shearing planes do not develop, and the deformation is largely by folding, it is possible that the folding dies out below by affecting successively narrower and narrower belts. Though such a process would make the deformed block taper downward, just as in the preceding case, the borders would be much less sharply defined. With increasing resistance to deformation with increasing depth, in accordance with the results of the experimental work of Adams and his colleagues,[3] it seems mechanically logical that folds should die out in this fashion. But whatever the nature of the bordering zones of accommodation may be, the results of the computations in the case worked out show that the folded tract becomes narrower

[1] G. A. Daubrée, *Études synthétiques de géologie expérimentale*, T.I., p. 316, Plate II.

[2] R. T. Chamberlin and W. Z. Miller, "Low Angle Faulting," *Jour. Geol.*, Vol. XXVI (1918), pp. 1–44.

[3] Frank D. Adams, "An Experimental Contribution to the Depth of the Zone of Flow in the Earth's Crust," *Jour. Geol.*, Vol. XX (1912), pp. 97–118; F. D. Adams and J. A. Bancroft, "On the Amount of Internal Friction Developed in Rocks during Deformation, and on the Relative Plasticity of Different Types of Rocks," *Jour. Geol.*, Vol. XXV (1917), pp. 597–637.

below, thus maintaining the general wedge shape. The deepest folds lie beneath the middle of the belt.

In the broader study of diastrophism it is to be recognized that movement is not wholly confined to the strongly deformed masses, but takes place in some less degree in the masses that lie below them and at their sides. Associated movements are to be recognized which extend deep into the earth and possibly even throughout its whole mass. The relations between the distinctly distorted section and the environing portion are various. For example, the bordering thrust-faults on the margins of the southern Appalachians and of many other strongly compressed mountain ranges indicate that actual fracturing and shear take place very commonly between the strongly deformed and the slightly deformed blocks near the surface. Where the deformation has not been so intense, a sharp upturn of the strata in a great fold may mark the borders of the mountainous belt, as at Tyrone, Pennsylvania, and in the Colorado Rockies. Here actual fracture has not developed to any important extent, though there has been an approach toward fracture on the outer limbs of such folds. The adjustment between the more movable, more deformed portion and the less movable, less deformed region has been accomplished, partly by shearing and partly by mass rearrangements taking place in the folding process. With increasing depth below the surface, actual faulting should diminish, though distributive shear should presumably descend much deeper. No limiting depths can be assigned, for the time element plays an important part, though not easy to evaluate. To quick-acting stresses the earth reacts as an elastico-rigid body; under long-continued stresses it yields to slow mass movement. With greater depth molecular rearrangement and recrystallization should presumably take precedence. These might be manifested by folding, or by cleavage, or perhaps only by rock flow. Under such conditions the deformed block would probably not be sharply bordered.

While the border belts near the surface are in places actual fault planes, nevertheless, throughout most of their extent they probably constitute zones, perhaps of considerable breadth, separating the more deformed mountain mass from the less deformed

mass to the side of it and below it. The accommodation may take place by differences in the amount of wrinkling on the two sides, differences in the extent of elongation and schistosity, or differences in some less clearly defined type of rock flow. It may be merely a zone in which, as one goes from the undeformed region into the crumpled mountain belt, folding rapidly becomes more pronounced and an increase in schistosity becomes marked. The dividing belts may be vaguely outlined or they may be more sharply defined.

Because the wedge shape seemed to be in general harmony with certain recognized facts and principles, it was natural enough to suspect that it might prove to be a type of diastrophism of wide application. Wedge dynamics might prove to be characteristic of other mountain systems, and might be applied perhaps also to the elevation of plateaus, and those movements which control the rise of continental masses. A plateau-forming movement, if the outcome of lateral thrusting, would be assigned to a thick shell gently wrinkled. Very little shortening of a still deeper section would suffice to elevate a mass of continental dimensions.

In 1910, following the publication of the Appalachian paper, an attempt was made to apply these principles to continental diastrophism. Cross-sections of the globe were drawn with border planes dipping inward beneath the continents at 45°. Because of the curvature of the earth, each plane, in order to carry out the principle consistently, was drawn to cross the different radii of the globe at 45°. The result of such a treatment is shown in Figure 1. Outlined thus, the continents appear as shallow units very subordinate to the oceanic segments. The latter are truly the master segments, which squeeze the continental wedges periodically outward, as well as laterally, when the materials of the contracting globe become strained beyond their yielding point.

This suggested extension of the wedge principle to the continents was not pushed farther at the time, for the reason that certain possible objections quickly came to mind, so that it seemed advisable to allow the question to lie fallow for a while and await developments. After a wait of ten years, during which time this principle was discussed with several successive classes of graduate students,

and during which time geologic thought has progressed more and more toward the conception of a solid globe, it now seems worth while to put the ideas briefly into print. Objection will, of course, at once be made by many to any prolongation of shearing planes

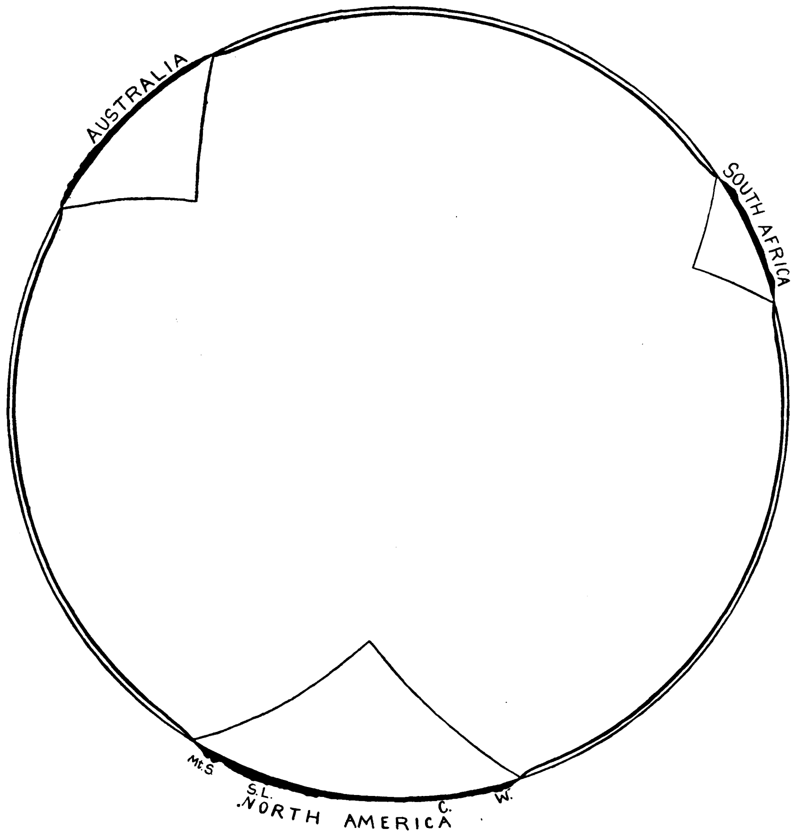

FIG. 1.—The continental wedges. Section through Washington, Chicago, Salt Lake, Mt. Shasta, Australia, and South Africa. Surface relief exaggerated and diagrammatic. Drawn in 1910.

deeply beneath the surface. The tenacity of the idea of easy flowage in the depths is remarkable. The idea of a molten interior, though disclaimed in name by most of those who follow closely the development of geologic science, is yet followed unconsciously, in fact, to some degree at least by most of them. On the other hand,

it is the view of those inquirers who accept the modern evidences of increasing solidity with increasing depth that the idea of easy movement in the interior is to be scrupulously avoided, whatever may be the form or mode of movement. It is held by them that differential motion of all kinds in the solid interior takes place only in response to high differential stress. If the term flow is to continue in use, it should carry simply the idea of an intimate distributive method of deformation and be shorn entirely of all suggestion of easy movement, for that belongs to liquidity. Strong support for this view is found in the experimental work of Adams, which extends the zone of cavities to greater depths than formerly supposed possible, owing to the increasing strength of the rocks under cubical compression.

There are increasing grounds for the view that the various special methods of deformation have a more intimate association with one another than has been generally recognized, and that processes heretofore confined to the upper zones may have application to greater depths. The true status of present knowledge of the movements in the deeper unseen zone has been most judiciously and trenchantly stated by Leith in his vice-presidential address before Section E of the American Association:[1]

> Notwithstanding these and other considerations, any conclusion as to the existence of a deep zone in which all rocks flow when deformed is hypothesis, not proved fact, and perhaps will always remain so. The environmental conditions are not accurately known; and even if each of the factors were measured, their conjoint effect is still speculative. Variations in the time factor alone may determine whether a rock flows or fractures. Rock flowage which has occurred in rocks now accessible to our observation fails to indicate increase with depth with sufficient clearness and definiteness to warrant confident downward projection.

The general purport of the under-configurations developed by these shell studies carries at least an intimation that the principles of surficial diastrophism are to some extent applicable to the deeper problems of the continents as well. When the ocean basins sink and the continents are uplifted, some adjustment necessarily takes

[1] C. K. Leith, "The Structural Failure of the Lithosphere," *Science*, Vol. LIII (1921), pp. 195–208.

place between the segments. Near the surface the adjustment may well be accomplished by thrust-faulting; by movement along distributed shear planes where clear-cut faulting does not develop; by accommodative folding, and in part by the deformation involved in the formation of flow cleavage, and possibly in other ways. It is important to understand clearly that the border zones between the more deformed blocks and the less deformed blocks are not held to be simple fault planes, though thrust-faults do so commonly emerge at the surface in these situations, but instead are held to be zones of more composite nature in which adjustments between the larger units are accomplished in the various ways outlined above.

In full agreement with the view that the results of deformation, in the zone of observation, afford perhaps the best criterion we have at present for judging of the behavior in the deeper zones, we may make the projecting planes, or zones, between the oceanic and continental segments the line of approach to the deeper problem, especially if the problems of the deeper horizons are as strictly the deformations of solids as are those of the surface, however different their conditions of temperature and pressure. With depth, fracture should become an exceptional phenomenon, though certain types of shear should be more persistent. And it would seem likely that deformation by distributive movement involving crumpling, cleavage, and general rock flow, should predominate in the deeper horizons.

Cleavage, by recrystalization, develops parallel to the elongation of the mass, whatever be the nature of the compressive stress which produces it.[1] From the experiments of Daubrée[2] upon the orientation of mica flakes under various conditions of compression, we learn that the direction of elongation is determined by the direction of least resistance. The deformation is controlled by the difference between the stresses along greatest and least axes of stress, and in this the least axis of stress is most important. By changing the position of the orifice (direction of easiest relief) in a compression cylinder, such as that used by Daubrée, *without changing*

[1] C. K. Leith, *Structural Geology* (1913), pp. 84–87.

[2] *Op. cit.*, pp. 407–22.

in the least the direction of applied force, the mica flakes could be made to assume any desired orientation. This illustration is introduced here for the reason that geologists so commonly refer to the direction of applied force as though it of itself determined the result, and relate everything to this direction without considering with equal care the lines of resistance. But it is the differential stress which is all important in deformation, and in this the axis of least compressive stress plays a part of the most critical importance. In fact, "lines of least resistance" might well be made the topic of a hortative sermon.

When a region is subjected to strong compressive stress under ordinary conditions, the axis of least stress is the vertical one, and the easiest relief is upward. Elongation then presumably takes a vertical direction, as does also whatever flow cleavage develops. But under conditions of special burden, lateral elongation may be a condition precedent to a final vertical one. A notable shear zone extending obliquely downward on the 45° principle, such as is here postulated between segments, might be expected to exert an orienting effect on the direction of most ready relief for some distance beyond the point where actual shear ceases, though it is uncertain how far beyond. After that influence ceased to be effective, the inclination of the ensuing schistosity should theoretically become more nearly vertical. If, in the deeper parts, the border planes between the segments come into parallelism with the elongation under recrystallization, and so with the schistosity, they should become steeper below. But it is not certain that the parallelism exists, nor do we know the controlling conditions sufficiently well to be certain that the elongation of the mass will be straight upward.

In the actual drawing of the border planes, the angle of 45° serves largely as a convenient average inclination, suggested by the planes of no distortion in the ellipsoid of strain.[1] It is, however, recognized in engineering practice that the angle of fracture under compressive stress, even where the strain is entirely non-rotational, varies widely from 45°, depending upon the nature of the

[1] C. K. Leith, *Structural Geology* (1913), pp. 16–20.

substance.[1] This variation applies especially to rupture, and it is uncertain how deep rupture may be safely projected. In rock flowage other conditions obtain. The inclination might be expected to become steeper. If it be true that in the lower reaches the border zones should become more steeply inclined than here drawn, that would amount to projecting the roots of the continental masses to greater depths. But the real significance of the location and behavior of the bordering zones in the deeper portions of the globe can only be satisfactorily treated by tracing the diastrophic phenomena throughout the stages of the earth's growth. Under the plantesimal view, each of the stages involved at first surficial diastrophism and later underwent the various deeper diastrophisms involved in the upgrowth of the continental and oceanic segments. This will be taken up in a later paper of this series.

According to the general philosophy of which the wedge theory is a part, condensation of material in favor of greater density takes place throughout the deep interior under the influence of gravitative force. This causes shrinkage and the development of strong lateral thrusting in the outer portion of the globe. When the growing stresses reach and exceed the strength of materials under the conditions obtaining within the earth, a period of diastrophism sets in. The vaster and heavier oceanic segments take the lead in descending and as they do so, the continents, several or all, are wedged upward. Some may be wedged up more than others, or one side of a continent uplifted more than the other sides. A moderately thick shell forming only part of a continent may suffer notable shortening and be pushed up into a plateau. A thinner shell along the borders of a continent, yielding more readily and suffering much greater shortening, may be folded and faulted into a mountain system. The tangential compressive stresses necessarily extend throughout the outer portion of the globe and are not to be thought of merely as thrusts from an active oceanic mass against a passive continental mass, but the actual deformation into mountain systems is, for reasons to be brought out later, a

[1] Walter H. Bucher, "The Mechanical Interpretation of Joints," *Jour. Geol.*, Vol. XXVIII (1920), pp. 707–30; Vol. XXIX (1921), pp. 1–28.

distinctly localized phenomenon occurring where the compressive stresses exceed the strength of materials.

In conclusion, it is felt that the shell-deformation is intimately related to the less obtrusive diastrophism of the subshell mass. The plunging zones that form the common border of the interlocking tracts give suggestive intimations that may have wider application and more profound significance. These form a line of approach to the larger diastrophic problem and so properly constitute a part of the groundwork for the study of megadiastrophism.